MONITORING THE SPATIALLY AND TEMPORALLY COMPLEX ACTIVE DEFORMATION FIELD IN THE SOUTHERN BAY AREA

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Progress Report for FY 2002 Activities

This report covers the activities of the second year of our two-year investigation. The work described is being undertaken by the principal investigator, Roland Bürgmann, graduate student Ingrid Johanson and BSL researcher Robert Nadeau. The research is composed of collection and analysis of space geodetic data (GPS and InSAR), analysis of micro-earthquakes for fault-slip information, and modeling and interpretation of those results in the context of fault slip rates, the locked or aseismically creeping nature of individual segments of the southern Bay area fault system, and earthquake potential from those faults.

1. Investigations Undertaken

The southern Bay Area is a structurally complex region of the North American-Pacific plate boundary. North of the creeping section of the San Andreas Fault (SAF) near the town of San Juan Bautista (SJB), the Calaveras Fault (CF) diverges from the SAF and fault slip from the creeping section is partitioned between the two. Plate motion is also accommodated on the active Sargent and Quien Sabe faults. After the SAF/CF junction, both faults transition from creeping to fully locked. North of the transition zone, the SAF last slipped in the 1906 earthquake and represents a significant seismic hazard. This region also contains the epicentral region of the 1989 Loma Prieta (LP) earthquake which occurred in the Santa Cruz Mountains on a secondary fault close to the SAF. The LP earthquake accelerated deformation rates throughout the southern Bay Area for 5-6 years, including regional deformation from exponentially decaying afterslip, increased compression within the Foothills thrust belt (Bürgmann, 1997b) and increased slip on the Pajaro section of the SAF, just north of SJB (Wilber and Bürgmann, 1999). The effects of the Loma Prieta earthquake are still felt on the Calaveras fault, where surface creep has yet to return to its pre-LP rate. Time dependent deformation also occurs in the form of creep events and slow earthquakes; primarily located in the area of the SAF that accommodates its transition from freely creeping to the southwest to locked northwest of San Juan Bautista. Geodetic measurements of strain redistribution due to these events are important for calculating their contribution to the slip budget and evaluating the potential for stress triggering of seismic events.

We yearly occupy our Global Positioning System (GPS) network in the southern Bay area, spanning the epicentral region of the Loma Prieta earthquake, the Calaveras fault and it's juncture with the San Andreas fault. This year, we extended the network further into the creeping section of the SAF. The GPS data are integrated with other data sets such as the creepmeter records on the Hayward, Calaveras and San Andreas faults (Data collected by USGS, and CU Boulder) and borehole strain data from instruments installed near San Juan Bautista (CSIRO and USGS). Interferometric synthetic aperture radar (InSAR) has been effectively integrated with GPS data to perform a joint inversion for slip on the Hayward fault (Bürgmann et al., 2000). Although the use of InSAR in the southern Bay Area has been hindered by large amounts of decorrelation noise (Johanson and Bürgmann, 2001), it has become a feasible data source through our implementation of a statistical-cost network-flow unwrapping algorithm (Chen and Zebker, 2001) and a novel data stacking approach (Johanson and Bürgmann, 2002). We are also pursuing subsurface slip rates on creeping members of the SAF system using repeating micro-earthquakes. Observations of recurrence intervals of identical micro-earthquakes to infer variations in slip rate on the fault surface (Nadeau and McEvilly, 1999). Bürgmann et al. (2000) applied this technique to the northern Hayward fault and found evidence for aseismic slip throughout all depths of the segment, further substantiating the results of a formal inversion of GPS and InSAR data. We are applying observations of repeating mirco-earthquakes together with InSAR to determine the amount of slip and extent of rupture in a 1998 slow earthquake (SEQ) on the SAF near San Juan Bautista.

The primary objective of this project is to monitor the spatially and temporally complex active deformation field in the southern Bay Area. This report will focus on three aspects of this investigation:

- Status of GPS measured crustal deformation.
- The use of InSAR to measure regional deformation and fault creep.
- The use of InSAR and repeating micro-earthquake data to detect and characterize transient slip events in the transition zone of the SAF.

2. Results

GPS measurements in the southern Bay Area

This year we included seven additional campaign sites (Figure 1); increasing the density of stations near the SAF/CF junction and expanding our network further into the creeping section of the SAF. The new sites were previously occupied as a part of CalTrans' High Precision Geodetic Network (HPGN) in 1991 and 1994. We will be able to exploit this pre-existing data to estimate a station velocity, with only one occupation of our own. We expect these additions to provide us with more information on the transition of the SAF from locked to creeping and on the role of the Paicines fault.

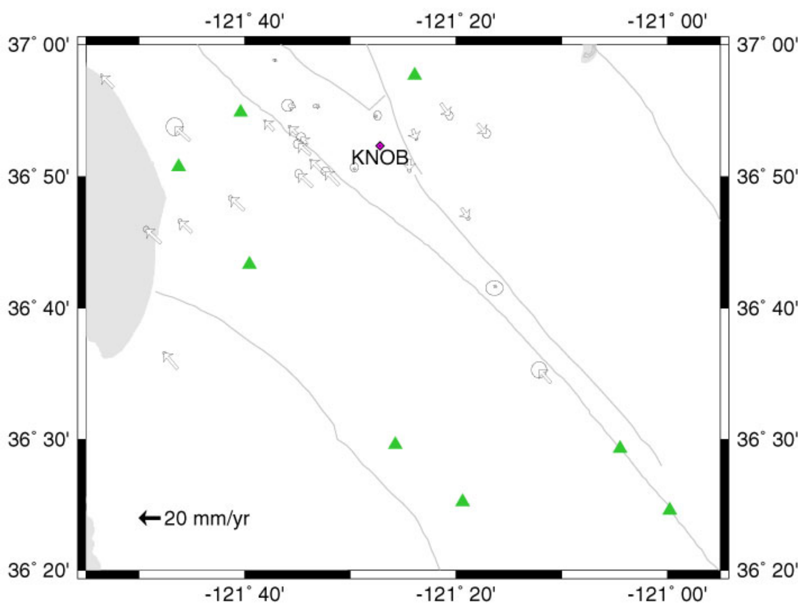

Figure 1. Compilation of continuous and campaign GPS derived velocity field in the SAF-Calaveras juncture area. Data are from our own and USGS measurements. The displacement field is shown relative to station KNOB outside the town of Hollister. Green triangles are stations added to the GPS network this year.

Recognizing the importance of integrating our data with other sources, we have made the decision to change our GPS processing routine from using the Bernese GPS processing software to GAMIT/GLOBK. The benefits of GAMIT/GLOBK include the ability to easily add in other GPS solutions of the continuous mode global IGS networks and BARD network by SOPAC (at UCSD) and the BARD processing center (at UCB) or campaign mode data from other investigations. We have processed all data from 2002 using this routine and we intend to reprocess all data from previous years back to 1994. In the near future, GAMIT format h-files of daily solutions will be available for the Southern Bay Area campaign network beginning in 1994.

Station velocities shown in Figure 1 are from data collected between 1991 and 2001 and processed with Bernese GPS processing software from the University of Bern. Figure 1 uses campaign mode data collected by the University of California, Berkeley and the USGS as well as data from continuously operating BARD sites. An interesting feature of the data is the continued localized displacement gradient across the Calaveras fault despite the absence of surface creep since the Loma Prieta earthquake (Manaker et al., 2002, J. Geophys. Res., in press).

Regional deformation in the southern Bay Area from InSAR measurements

Fault motions in the southern Bay Area include significant amounts of surface creep and shallow transient slip. This requires geodetic measurements to be closely spaced around the slip patch in order to adequately determine basic parameters such as slip surface area and depth. Even with the expansion and densification of our campaign GPS network in the past several years, stations are generally spaced more than 10 km apart, making it difficult to detect the deformation field of a shallow event from point measurements alone. Space-based Interferometric Synthetic Aperture Radar (InSAR) can map ground deformation at 10s-of-meter spatial resolution with sub-cm precision. The improved spatial resolution makes InSAR an excellent tool for observing shallow fault movement with small deformation rates such as along-strike creep rate variations as the SAF transitions from locked to fully creeping and the 1992, 1996 and 1998 sequence of slow earthquakes on the SAF near San Juan Bautista (SJB).

Surface displacement is computed from the interferograms by converting the phase delay between scenes into line-of-sight range change rates. Surface displacements and resulting range change are related as $\Delta\rho = \Delta\vec{d} \cdot \vec{e}$, where $\Delta\rho$ and $\Delta\vec{d}$ are the range change and surface displacement vectors, respectively, and $\vec{e}$ is the unit vector in the range direction (Bürgmann et al., 2000). We process interferograms using the Repeat-Orbit Interferometry Package (ROI-Pac) developed at the Jet Propulsion Laboratory and the Statistical-cost Network-flow Algorithm for Phase Unwrapping (SNAPhU) developed at Stanford University (Chen and Zebker, 2001).

With its good spatial resolution and high precision, InSAR is capable of detecting small areas and small amounts of deformation. However, areas with vegetated ground cover, like most of the southern Bay Area, are very susceptible to decorrelation noise. The interferograms covering this area often contain only small isolated patches of coherent signal. Our data processing strategy is therefore driven by the goal of maximizing the spatial coverage of each interferogram. We have begun this year to include SNAPhU in our processing routine; this algorithm preserves small patches of coherent phase and provides a rigorous estimation of the phase cycle offset between them.

Atmospheric delays are also a major error source for InSAR. Atmospheric errors are considered random in time and can therefore be minimized through data stacking. In an attempt to again maximize the spatial coverage of useful data, we have implemented a novel approach to data stacking. We allow the data sources (input interferograms) to vary from pixel to pixel, including only those sources with coherent data at that point and only those points with data from three or more sources. Each pixel is then weighted according to the time spanned by its inputs. Figure 2 shows the result of stacking nine input interferograms using data from the European Space Agency's ERS 1 & 2 spacecrafts from 1995-2000 (Track 299 Frame 2861). Figure 2b actually contains greater spatial coverage than any of its individual input interferograms. Figure 2c illustrates the number of images with coherent data available at each point.

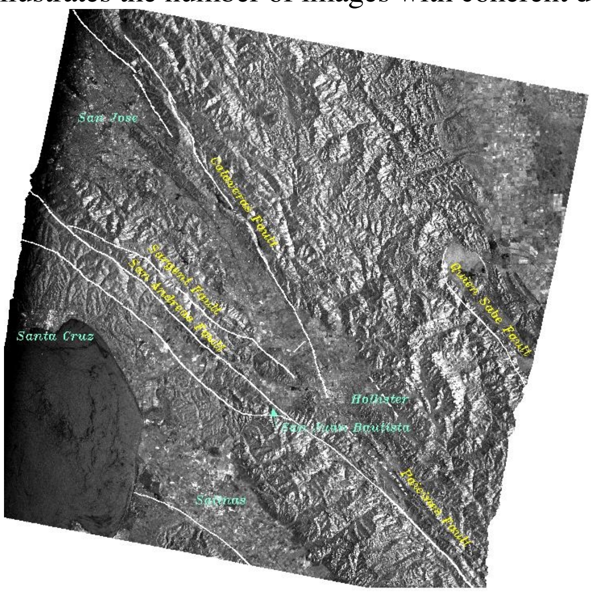

Figure 2a

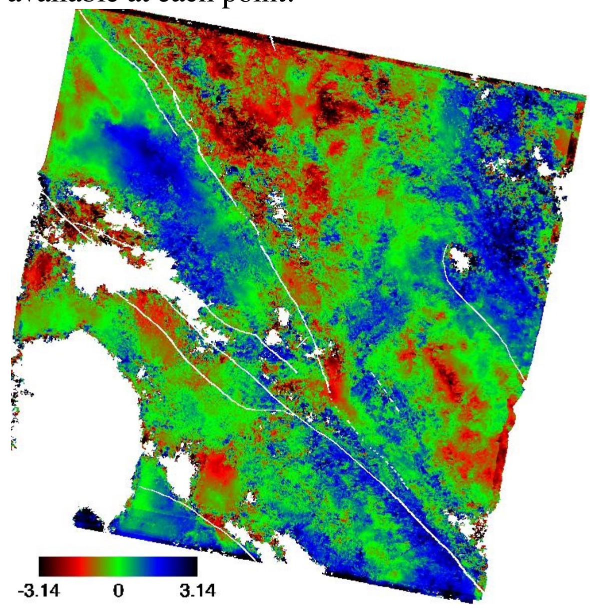

Figure 2b

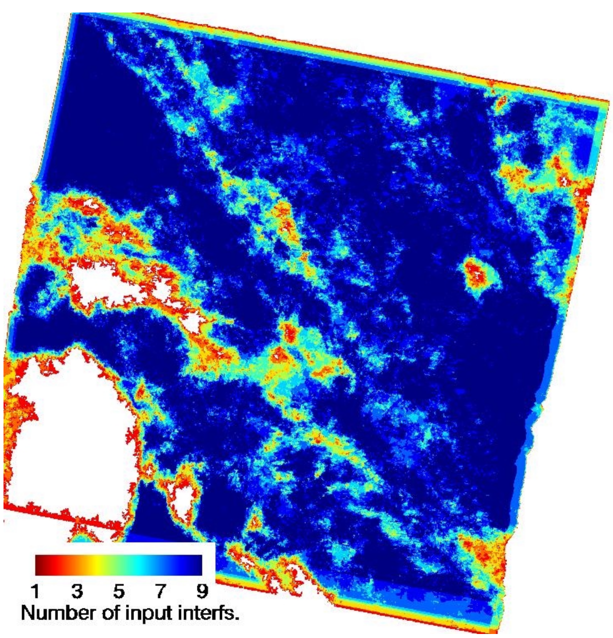

Figure 2c

Figure 2 a) Amplitude Image for Track 299 Frame 2861 with regional faults shown as white lines. North is oriented towards the top of the image. b) Stack of nine interferograms spanning 1995-2000, scaled to one year. Range change is in units of radians, with negative numbers representing movement toward the satellite (uplift or southeast motion). c) Coverage map showing the number of interferograms with coherent data at each point. Points with greater than three available inputs were included in Figure 2b.

The 1998 Mw 5.3 Slow Earthquake

With the increase in continuous GPS sites, slow earthquakes (SEQs) have been observed on faults all over the world, especially deep in subduction zones. To date, the SAF near San Juan Bautista is the only location where slow earthquakes have occurred on an accessible strike-slip fault. The slip in these events was much closer to the surface than in subduction zone events, making this a unique and potentially very effective location to study the mechanics of slow slip. Creep- and strain-meters have been the primary instruments to record SEQs in this area (Linde et al., 1996). Gwyther et al. (2000) report on the location, geometry and magnitude of one such event in August of 1998 as determined from these sparsely located instruments. We hope to better constrain the slip parameters by combining the high spatial resolution of InSAR with direct measurements of subsurface slip rates from repeating earthquake sequences.

Figure 3 shows two interferograms spanning the 1998 slow earthquake. Each exhibits a linear phase gradient aligned with the fault trace. If the signal is attributed to purely strike-slip motion, the interferograms both indicate right-lateral slip of about the same amount as recorded by creepmeters (Johanson and Bürgmann, 2002). It is expected, however, that the measured range change will contain some vertical motion. We are working on incorporating ascending track frames into this analysis to separate vertical and horizontal motions. In Figure 3b and 3c, the across-fault phase change continues to the south, possibly indicating a larger slip patch than was determined with creep- and strain- meters.

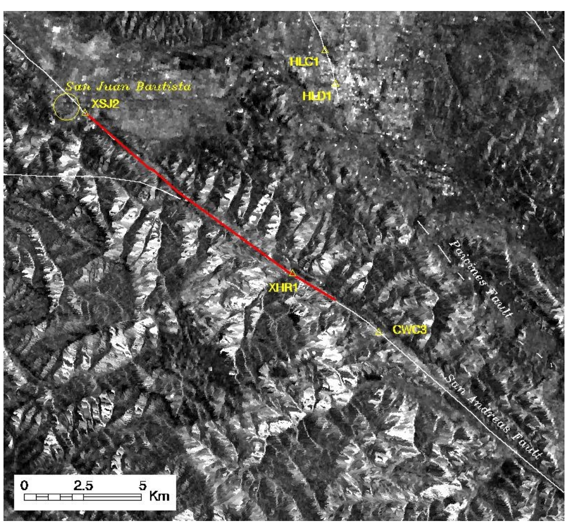

Figure 3a

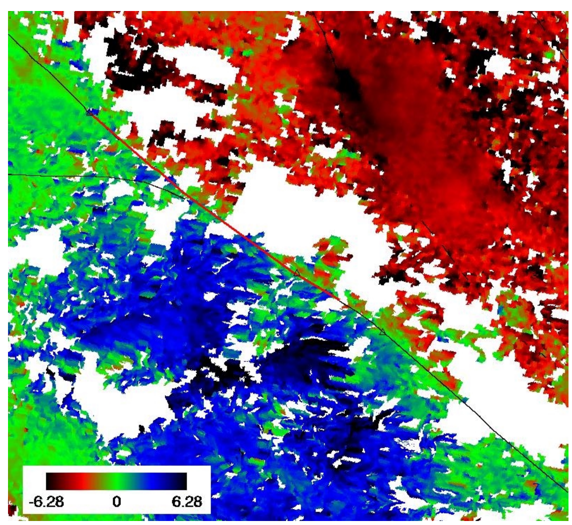

Figure 3b Aug. 18, 1997 – Oct. 12, 1998

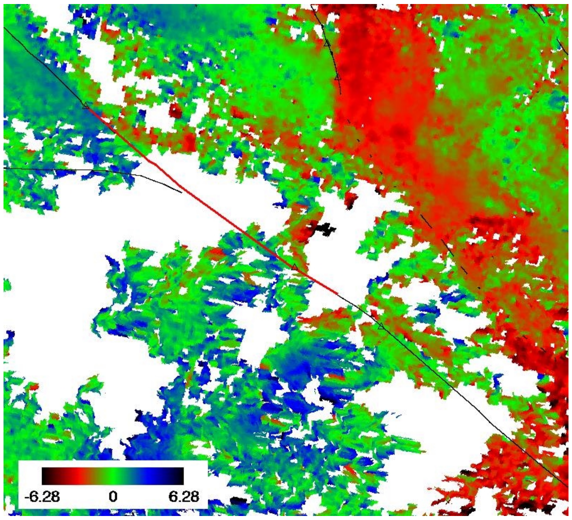

Figure 3 a) Amplitude image – subsection of Track 299 Frame 2861. Major faultlines are shown in white, red line is the length of fault rupture in the 1998 SEQ as reported by Gwyther et al. (2000) from creep- and strain-meter records. Triangles are the locations of creepmeters in the area. b) Interferogram spanning 1.15 years with a perpendicular baseline of 69 m. Range change is in units of radians, with negative numbers representing movement toward the satellite. Black lines are regional faults and red lines are same as Figure 3a. c) Same format as Figure 3b. Interferogram spans 0.96 years and has a _l_ baseline of 109 m.

Figure 3c June 29, 1998 – June 14, 1999

We also attempt to use sub-surface slip rates determined from repeating micro-earthquakes to better define the rupture plane. Slip from the characteristic quakes reflects fault deformation at depths of up to 10-15 km and is a more direct observation of tectonic slip on the fault than are surface creep and other surface based measurements. In Figure 4, the color of each point indicates the amount of slip required to produce the observed clock advance (or delay) of a repeating micro-earthquake, assuming a time-predictable model.

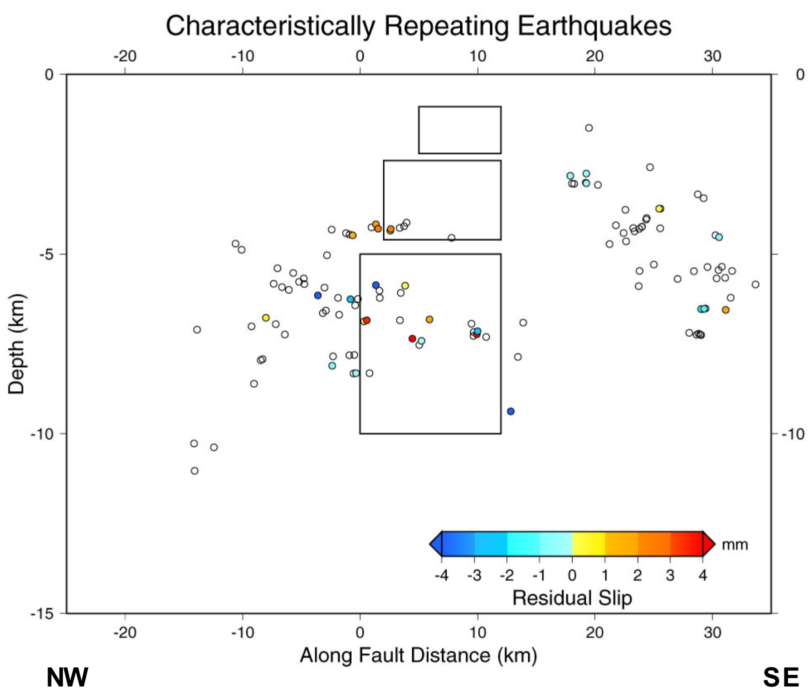

Figure 4: Circles are locations of repeating earthquakes sequences on the SAF. Open circles have no data after 1998. Colored circles represent the slip surrounding the repeating earthquake rupture patch required to produce the observed clock advance or delay (negative slip) in the first occurrence of a repeating earthquake after the 1998 SEQ. All slip contributing to the clock change is attributed to the 1998 SEQ. Shown in black are the outlines of slip patches for the 1998 SEQ obtained by Gwyther et al. (2000) from creep- and strain-meter records.

The occurrence of a slow earthquake could affect characteristic earthquake sequences in two ways. First of all, if the slip patch of a characteristic earthquake in the slow earthquake rupture zone does not slip during the SEQ, then the repeating earthquake will experience a clock advance proportional to the SEQ's slip. However, if the slip patch of a characteristic earthquake experiences slip during the SEQ, then we can consider its "clock" to be reset and the next earthquake in the repeating earthquake sequence will be delayed. We would therefore expect extreme values (of either sign) of residual slip in the slow earthquake rupture area. In Figure 4, extremes of both negative and positive values occur in the rupture area of Gwyther et al. (2000) for the 1998 SEQ. By contrast, only small residuals were found for events to the southeast, well outside the SEQ rupture area. The lack of repeating earthquake below 8 km in this area does not allow us to put a depth constraint on rupture. However, the occurrence of significant residual slip to the northwest may indicate that the rupture extending further in that direction than is shown.

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3. Non-technical Summary

We use the Global Positioning System (GPS), Synthetic Aperture Radar Interferometry (InSAR), and repeating identical micro-earthquakes to gather information on crustal deformation and earthquake hazard in the southern San Francisco Bay region. Most of the transient deformation associated with the 1989 Loma Prieta earthquake apparently ceased by about 1994. However, transient deformation anomalies such as slow earthquakes persist on the San Andreas Fault in the region of transition from locked to creeping behavior and likely influence the stress and thus earthquake potential in the region.

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6. Data Availability

Raw and RINEX formatted GPS data files for static surveys of markers in south San Francisco Bay area from 1994-2002. These files typically include greater than six continuous hours of data, recorded at a 30 s collection rate with a 10-degree elevation mask. These data are freely available through the UNAVCO archive facility in Boulder, and also at the University of California, Berkeley. Photocopies of survey log sheets and site descriptions are also available. Additional data used in this study included RINEX format files obtained from the U.S. Geological Survey and the Bay Area Regional Deformation Network (BARD). These files include campaign-style surveying (USGS) and continuous GPS stations (BARD) and are available at the NCEDC at UC Berkeley.

For more information regarding data availability, contact:
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